Properties of Magnetoinductive Resonator Array for MRI Application

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Abstract. *A method for partial resonant frequencies measurement of the magnetoinductive array is described. The method utilizes a return loss measurement of a coil probe and it allows to verify the mutual adjustment of the resonant frequencies. The effective permeability evaluation of the array is presented and results of numerical analysis are shown. Numerical analysis results are compared to the experimental results. It was found that at the resonant frequency the signal from the resonator array is suppressed due to the very low real part of the permeability.*

Keywords: Periodical Structure, Resonator Array, Nuclear Magnetic Resonance

1. Introduction

A possibility of manipulation of magnetic field distribution in magnetic resonance (MR) systems has been shown in recent works [1]. Some approaches consider this phenomenon as a subwavelength imaging which can be observed with metamaterial slabs. In contrast to classical metamaterial imaging concept, which utilizes double negative synthetic material, an exploitation of metamaterial slab with only negative permeability or only a negative permittivity is possible. The typical characteristic of metamaterials structures is the dimension relation between the metamaterial slab components and the wavelength of the wave which is to carry through the slab. The dimensions of metamaterial components are much smaller than the wavelength of the interest. In spite of this dimension disproportion the metamaterial structures show response at these wavelengths. Regarding to these dimension relations it can be found that the metamaterial structure-wave interaction is in the realm of quasi-static fields. This phenomenon allows consider only electric or magnetic part for imaging purposes. In the case of magnetic imaging a progress has been made by Freire and Marques [2].

The main goal of manipulation of magnetic field distribution in MR systems is to increase the received MR signal which is a response to radiofrequency sample excitation. The preliminary concept of the magnetoinductive structure for experimental MR system has been proposed and built [3]. The lens components – a capacitance loaded ring resonators - are based on non-ferromagnetic materials. In spite of their insignificant response in the DC magnetic field, they exhibit magnetic response around a certain resonant frequency. The resonant frequency has to be close to the frequency of the excitation RF pulse. By suitable configuration of the components the imaging effect is expected and the device behaves like a magnetic RF field concentrator. In previous work [3] the theoretical approach to resonator arrays design has been presented. There has been presented some issues of the resonators fabrication and component selections. One of the goals is to achieve mutual resonant frequencies adjustment. The results have shown the need for careful resonators assembly. The suggested points of the design have been taken into the account in the next resonator arrays fabrication. The results of resonant frequencies measurement of improved resonator array will be presented in the paper. The partial resonant frequencies are examined by means of coil probe return loss measurement. In order to obtain a notion of resonator array behaviour two analysis steps has been performed. The first analysis step, a numerical simulation, gives an idea about the frequency dependence of array's effective permeability. The second analysis step consists in MR system measurement of field distribution in array vicinity.

2. Measurement of arrays partial resonant frequencies

The total frequency characteristic of the array consists of the superposition of partial resonant curves of each resonator, which are mutually coupled. Measurement of resonant frequency of magnetoinductive (MI) resonator array has been described in [3]. For the measurement of the single resonator resonant curve a method utilizing a small coil probe, directional coupler, frequency generator and spectrum analyzer has been proposed, see Fig. 1 (left part). The analyzer with built-in tracking generator and directional coupler has been used and the return loss of the small loop probe has been measured, Fig. 1 (middle part). The example of loop probe return loss is shown in the right part of Fig. 1 as a remarkable drop with dip level above 7 dB.

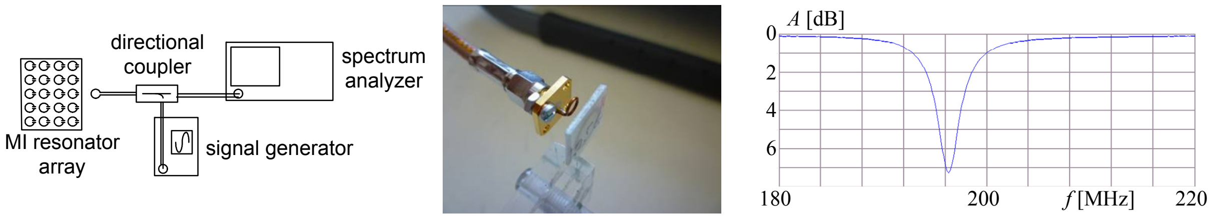
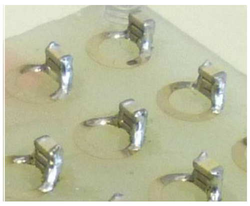


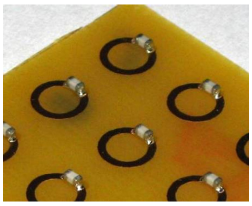
Fig. 1. Setup for resonant curve of single resonator measurement (left), the loop probe detail (middle) and an example of measured characteristic (right).



a)

197,88	193,49	195,37	196,16	195,69
196,00	193,00	199,16	197,26	194,58
199,14	196,47	194,90	197,10	197,57
195,69	194,12	196,17	196,95	196,94
194,43	196,16	198,52	193,80	193,49

b)



c)

198,04	198,67	197,73	196,63	198,20
198,51	200,24	197,26	196,78	197,41
198,51	199,45	198,04	198,35	198,04
197,26	198,98	198,82	198,35	197,73
197,24	198,67	197,41	197,73	198,35

d)

Fig. 2. Early MI array detail a) and its map of resonant frequencies in MHz b), new MI array detail c) and its map of resonant frequencies in MHz d).

3. Numerical analysis

As has been noted the resonator array shows a magnetic response around certain resonant frequency. Hence, the frequency dependence of array permeability exhibits typical resonant characteristic. In order to characterize the properties of the array the effective magnetic permeability may be used. To obtain an idea about the effective permeability characteristic a finite element method numerical analysis by means of Comsol system has been performed. The simulated structure consist of 3x3 array of resonators with outer diameter of 5 mm, inner diameter of 3 mm, thickness of 35 μm and ring spacing of 18 mm. The substrate with thickness of 2 mm has a dielectric constant of 4,5. The perfect electrical conductor (PEC) has been used as the ring. The capacitance of the resonators has been modeled in such a way, that to every finite element of the ring has been assigned a dielectric constant with suitable value. The total capacitance of the ring model was equal to the lumped capacitance 112 pF.

The structure has been excited by planar wave with a magnetic component H_y perpendicular to the array which is in plane xy. Following general wave equation has been solved:

$$\nabla\times\mu_{\mathrm{r}}^{-1}\left(\nabla\times\boldsymbol{E}\right)-k_0^2\left(\varepsilon_{\mathrm{r}}-\frac{\mathrm{j}\sigma}{\omega\varepsilon_0}\right)\cdot\boldsymbol{E}=0,\ \nabla\times\mu_{\mathrm{r}}^{-1}\left(\nabla\times\boldsymbol{H}\right)-k_0^2\left(\varepsilon_{\mathrm{r}}-\frac{\mathrm{j}\sigma}{\omega\varepsilon_0}\right)\cdot\boldsymbol{H}=0\,. \quad (1)$$

where μ_{r} is relative permeability, $\boldsymbol{E}$ is electric field intensity vector, k_0 is vacuum wave number, ε_{r} is relative permitivity, σ is conductivity, ω is wave angular frequency and $\boldsymbol{H}$ is magnetic field intensity vector. Considering the material relation $\boldsymbol{B}=\mu_{\mathrm{r}}\mu_0\boldsymbol{H}$, we can derive from the magnetic flux relation on the array surface a relation:

$$\iint_{\Omega}\boldsymbol{B}\mathrm{d}\boldsymbol{S}=\mu_{\mathrm{r}}\mu_0\iint_{\Omega}\boldsymbol{H}\mathrm{d}\boldsymbol{S}\,, \quad (2)$$

where Ω is a integration area specified as a array surface a d$\boldsymbol{S}$ is vector surface element. When we consider a wave magnetic field component H_y perpendicular to the array surface we can derive from (2) an relation for effective permeability μ_{eff} of the array:

$$\mu_{\mathrm{eff}}=\left(\iint_{\Omega}B_y\mathrm{d}S\right)\Big/\left(\mu_0\iint_{\Omega}H_y\mathrm{d}S\right), \quad (3)$$

where H_y is an excitation magnetic field intensity and B_y is an magnetic flux density on the array surface. The resultant frequency characteristic of the effective magnetic permeability is shown in Fig. 3. In Fig. 3a) is a real part of the effective magnetic permeability μ'_{eff}, in Fig. 3b) is an imaginary part of the effective magnetic permeability μ''_{eff}. Around the resonant frequency of the array a smaller frequency step has been used also and the analysis repeated. Fig. 3c) shows a decomposition of the total characteristic on partial resonances. Since identical parameters of the resonators have been used, this effect is probably caused by mutual resonator coupling and finite element size, which has been used.

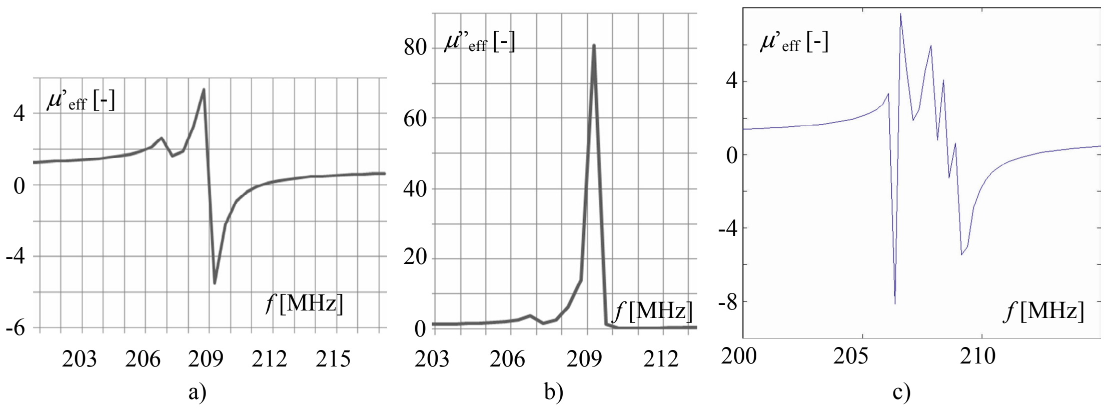
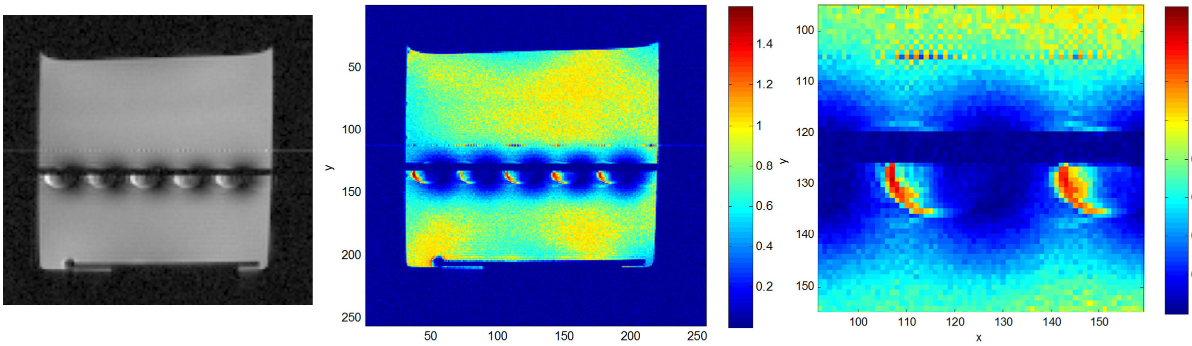


Fig. 3. Computed real part of the effective magnetic permeability μ'_{eff} a), imaginary part of the effective magnetic permeability μ''_{eff} b), detail of real part of the effective magnetic permeability μ'_{eff} computed with finer frequency step c).

4. Impact of the array on field distribution in MR cavity

Since the resonator array structure, which has been built (Fig. 2c)) exhibits a magnetic response on frequency close to the excitation frequency of the intended MR system, verification of the array's impact on field distribution has been proposed.

Result of numerical analysis in section 3 shows that at the resonant frequency of the array the real part of the effective permeability approaches to zero, while the imaginary part rises. This fact should cause the π/2 phase shift of the induced field in compare to the excitation field. Since the response detection of the specimen is evaluated regarding the initial phase, it may seem that for the close space around the resonator no response signal is present. The induced in-phase field of the resonators will be suppressed. For the verification of array's impact on the MR response an image acquisitions of water phantom with resonator array haves been performed. The array has been placed in the box with water. The plane of the array was parallel to the water surface, in plane *xz*. A transverse slice *xy* crossing the middle resonator has been acquired. The slice thickness was 2 mm. The magnitude image is shown in Fig. 4a). Fig. 4b) shows a field map which magnitude is related to magnitude of excitation field B_1. From Fig. 4b) is obvious that the response of the specimen is strongly suppressed around the resonators. A possible influence of the capacitor susceptibility may be observed as areas with increased magnitude, which is shown in detail in Fig. 4c).



a) b) c)

Fig. 4. Images of slice of array-water phantom configuration - magnitude image a), field map b), field map detail c).

5. Conclusions

It might be concluded that the results of experimental verification of resonator array's impact on the field distribution in MR cavity coincide with the numerical analysis results. The detected real part of the specimen response is strongly suppressed around the resonators. This evidences that the array's partial resonant frequencies were set very close to the excitation frequency of the MR system. To achieve a possibility of MR signal improvement and imaging properties of the array the resonator frequencies should be set close to the excitation frequency, which is going to be a matter of further research.

Acknowledgements

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